# FORMATION, QUANTIFICATION, AND PRESERVATION OF THE TRANSGRESSIVE STORM DEPOSIT OF HURRICANE IKE FORMED ALONG THE INNER SHELF OF GALVESTON ISLAND

A Thesis

by

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## ABSTRACT

In 2008, Hurricane Ike made landfall at Galveston Island, Texas, and caused significant impacts on the coastal environment. An assessment of the impact of Hurricane Ike on the shoreface and inner shelf sediments that occur offshore of the island was made by using seafloor bathymetric and acoustic backscatter data obtained by sonars together with information about seafloor sediments obtained by cores. Pre-storm data from surveys collected between 2001 and 2007 were compared to post-storm data collected during 2011 (no other hurricanes or tropical storms struck near Galveston during the time period when data were collected). Our results reveal the existence of bars containing between 1,800,000 $m^3$ – 3,000,000 $m^3$ of sand, in water depths ranging from 6.5 m and 10 m. The non-hurricane wave-base was estimated to be 5.8 m, placing these bars well below "fairweather" or non-hurricane wavebase.

Previous research on the sand flux to the shore face (4m-8m) estimate that 115,000+-28 $m^3\ y^{-1}$ of sand is sequestered along Galveston Island. For the sake of this study, I will use the upper limit of the Galveston Island sediment sequestration estimate of 143,000 $m^3\ y^{-1}$ as an estimate of annual sediment sequestration within the shoreface (0-10 m isobaths).

I hypothesized that the volume of sand within Hurricane Ike formed bars is significantly larger than the estimated average annual sediment sequestration of the shoreface of Galveston Island.

Using the average volume of the Hurricane Ike bars over the 4 year interval from 2007-2011, the average sediment sequestration for the interval below fairweather wave base is 750,000 $m^3\ y^{-1}$. This means that the volume of sediment contained within the Hurricane Ike bars is between approximately 3 and 5 times the estimated annual shoreface sediment sequestration, confirming the hypothesis. Measurements further reveal that the volume of sediment stored within the Hurricane Ike bars is almost twofold (1.8x) the estimation what would be required to maintain the beach under storm conditions. This volume is also approximately 2-3 times higher than the estimated sediment flux from Sabine Pass to San Luis Pass. It should be noted that this study does not include changes within the upper shoreface, which was also highly erosional, but only considers sand lost from the system by being transported offshore below the depth of fairweather wavebase.

## ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Dellapenna, and my committee members, Dr. Slowey, Dr. Highfield, and my Coastal Geology Lab coworkers, for their guidance and support throughout the course of this research.

Thank you to my friends and colleagues who helped make my experience at Texas A&M University worthwhile. Thank you to the department faculty and staff. I also want to extend my gratitude to the General Land Office, which funded much of the survey work.

Finally, thanks to my mother and father for their encouragement and to my wife Allie for her patience and love.

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# 1. INTRODUCTION

Understanding sediment transport, particularly to and from the shoreface, is needed for proper beach volume change analysis [*Morang*, 2006; *Vanderburgh et al.*, 2010]. Hurricanes provide forces much larger than the typical seasonal cycles and the extent of their influence needs to be refined [*Hayes*, 1967; *Morton*, 1988].

Hurricane Ike provided this rare opportunity to investigate the detailed impact of a direct hurricane strike on the shoreface and innershelf of a barrier island. Hurricane Ike struck Galveston Island, Texas with a storm surge greater than 4 meters and winds in excess of 175 kilometers per hour. Prior to Hurricane Ike, the last hurricane strike near Galveston Island was Hurricane Alicia in 1983. Since Hurricane Ike, there has been no hurricane or tropical storm to have impacted Galveston Island. Archived surveys conducted by the TAMUG Coastal Geology Research Laboratory between 2001-2007 provided pre Hurricane Ike data, and post-Hurricane Ike surveys were conducted in 2011, all between the 3-10 meter isobaths using side scan sonar, swath bathymetry. Submersible vibracores were collected in 2012 (Figure 1). The pre-Ike data were compared to data collected in 2011, three years after Hurricane Ike made a direct landfall on the study site. The pre-Hurricane Ike surveys reveal that prior to Hurricane Ike, the seabed was mud dominated and generally featureless. Post-hurricane Ike surveys show extensive coverage of large scour pits (~300 m wide) between the 5-8 m isobaths. Seaward of these pits, a 30 km long by 2 km wide sandy bar-trough system developed at an oblique angle to shore.

The hypothesis being tested is:  The volume of sand within Hurricane Ike formed bars is much larger than the estimated average annual sediment sequestration of the shoreface of Galveston Island. By testing this hypothesis an estimate of sediment transport related to the hurricane will be obtained.

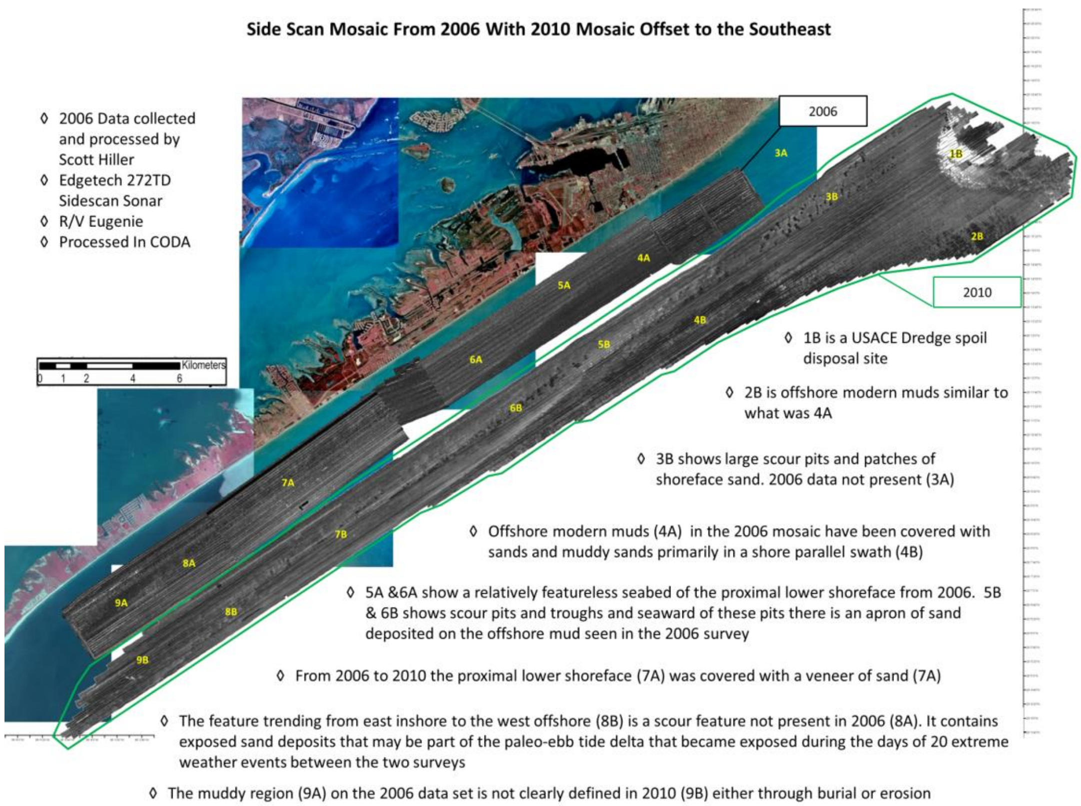



Figure: 1 Side scan sonar offset comparison: 2006 vs 2010

# 2. BACKGROUND

## 2.1 Galveston Island

Galveston Island is a uniquely situated barrier island on the upper Texas coast, approximately 80km south of Houston [*Giardino*, 1987]. It is part of an almost continuous barrier island chain that runs along the Northwestern coast of the Gulf of Mexico (GOM). Galveston Island extends over 40 km from the Bolivar Roads mouth of Galveston Bay to San Luis Pass.

Galveston Island has a 16 km (10 mile) long seawall, 5.2 m (17 feet) high that was constructed after the devastating 1900 Hurricane that destroyed much of the City of Galveston. Along with the construction of the seawall, much of the city was raised, with the area proximal to the seawall having the same elevation (5.2 m) and sloping towards the bay to reach less than a meter above sea level. The 29.5 km (18.25 miles) of island west of the seawall is referred to as the Westend and is not protected by the seawall and is a more “natural” barrier island setting.

According to the U.S. Census Bureau, the city of Galveston is home to 57k local residents and yearly generates $908.2 million through tourism, which accounts for 3.4% of Texas’ tourism GDP and one in three jobs in Galveston County [*Economics*, 2012; *Runyan*, 2013]. This economic value drives the discussion of beach sustainability and management in both terms of financial cost and environmental impact. Because of the economic impact, there is a multidisciplinary need to understand and accurately predict geologic changes in the nearshore environment. Additionally, state and federal recourses are used for beach nourishment and construction projects to help offset the high erosion rates seen in places along Galveston Island's shoreline. For example, just two of the General Land Office (GLO) and The Coastal Erosion Planning and Response Act (CERPA) ongoing projects along Galveston's seawall total over $9 million.

Galveston Island is one of the nation's most highly eroding shorelines, with annual rates over 1.5 m /year [*Anderson and Wellner*, 2002; *King*, 2007], and localized erosion rates up to 3.5m/year [*Anderson*, 2007; *Anderson et al.*, 1991; *King*, 2007; *Rodriguez et al.*, 2004]. These high rates of erosion are central to studies such as this one and are why the aforementioned nourishment projects exist. A better understanding of the source and sink pathways will lead to more efficient beach management, including identification of proximal sand banks for nourishment projects.

## 2.2 Hurricane Ike

Hurricane Ike was the 9th named storm of the 2008 season, the 6th hurricane to make landfall in the U.S., and the third time in two months the city council advised for evacuation. Hurricane Ike struck Galveston Island on September 13, 2008 at 2:10 am CTD as a very intense Category 2 Saffir–Simpson hurricane scale (SSHS) storm with sustained winds over 175 km/h, however the Integrated Kinetic Energy, fittingly shortened to IKE, registered 5.6 out of a 6 point scale [*Brown et al.*, 2009]. At its peak, on September 5th, Ike was a Category 4 hurricane with maximum sustained winds of

230 km/hour (145 mph) and a pressure of 935 mbar, making it the most intense storm in the 2008 Atlantic Hurricane season. At the time, Hurricane Ike was the 4th costliest storm in U. S. history at 19.3 billion in damages, and accounted for nearly half of the deaths of the 2008 hurricane season [*Blake et al.*, 2011; *Brown et al.*, 2009].

The storm surge from Hurricane Ike rose to approximately 4 m over the course of approximately 33 hours prior to making landfall, with winds primarily out of the south. The storm surge rose from both the bay and GOM sides of the island. Although heavily pounded by waves, the storm surge never rose above the seawall. For more than 10 hours prior to the storm's landfall, the storm surge was higher than 3.5 m and winds were in excess of 20 m/s (40 mph). As the eye of the storm passed, the wind velocity dropped from over 40 m/s to 2 m/s and rotated 180 degrees so that it was out of the north. The passage of the postfrontal eyewall hit with gusts as high as 40 m/s for nearly 4 hours and maintained gusts in excess of 25 m/s for an additional 8 hours (Figure 2).

The bayside of the island is far less protected than the GOM side of Galveston Island. There are extensive older waterfront neighborhoods with bulk-heads along the canals and a few with natural wetland interfaces. The explosive surge of the postfrontal eyewall of the storm resulted in entire bay front neighborhoods and business being completely destroyed. In addition, the storm surge ripped through much of the interior of Galveston Island from the bayside to the GOM side. Much of the storm surge receded very rapidly. This massive erosive force altered much of the shoreface and nearshore of Galveston Island, the extent of which is examined in this paper.

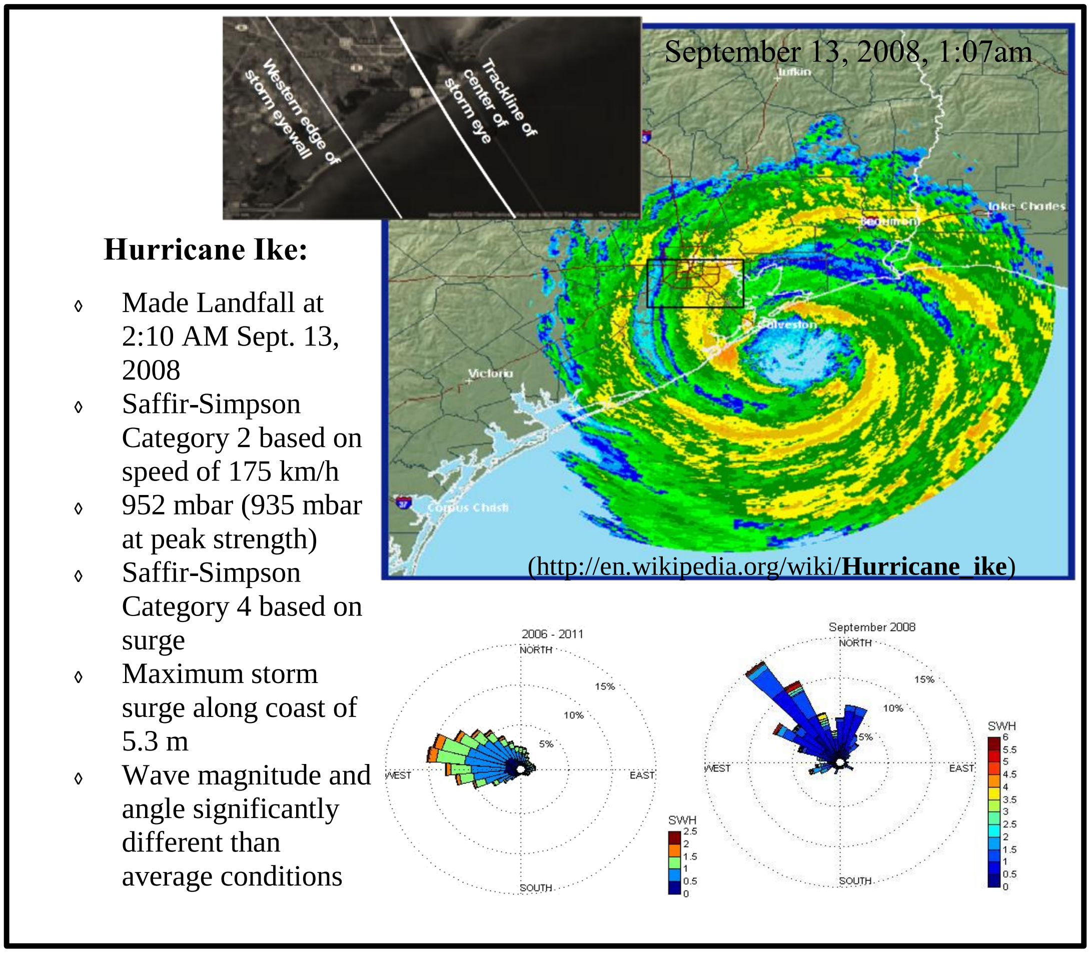



Figure 2: Hurricane Ike information, radar, path, and wind roses

## 2.3 Geologic Setting

Galveston Island is a barrier island situated on the southeast Texas Quaternary coastal plain, approximately 80 km southeast of Houston [*Giardino*, 1987]. It is part of an almost continuous barrier island chain that extends down the northwestern coast of the GOM [*Giardino*, 1987]. Galveston Island extends over 40 km from the Bolivar Roads mouth of Galveston Bay to San Luis Pass. It began formation during the Holocene low stand of sea level over 6,000 years ago as a sand bar [*Cole and Anderson*, 1982]. Overtime the island accreted both seaward and southwestward and formed the modern island. For most of its history, the Galveston barrier island system was prograding seaward, however, over the past 50 years, it has been in a state of retreat, moving landward at an average rate of 3 m/year [*Anderson and Wellner*, 2002; *Siringan and Anderson*, 1994].

The retreat of the island in the early 1900's has been influenced by several anthropogenic obstructions and physical processes, including the construction of the Galveston seawall system and installation of the South Galveston Jetty. Collectively, these alterations have resulted in altered sediment dispersal patterns and reduced the sediment supply to the island.

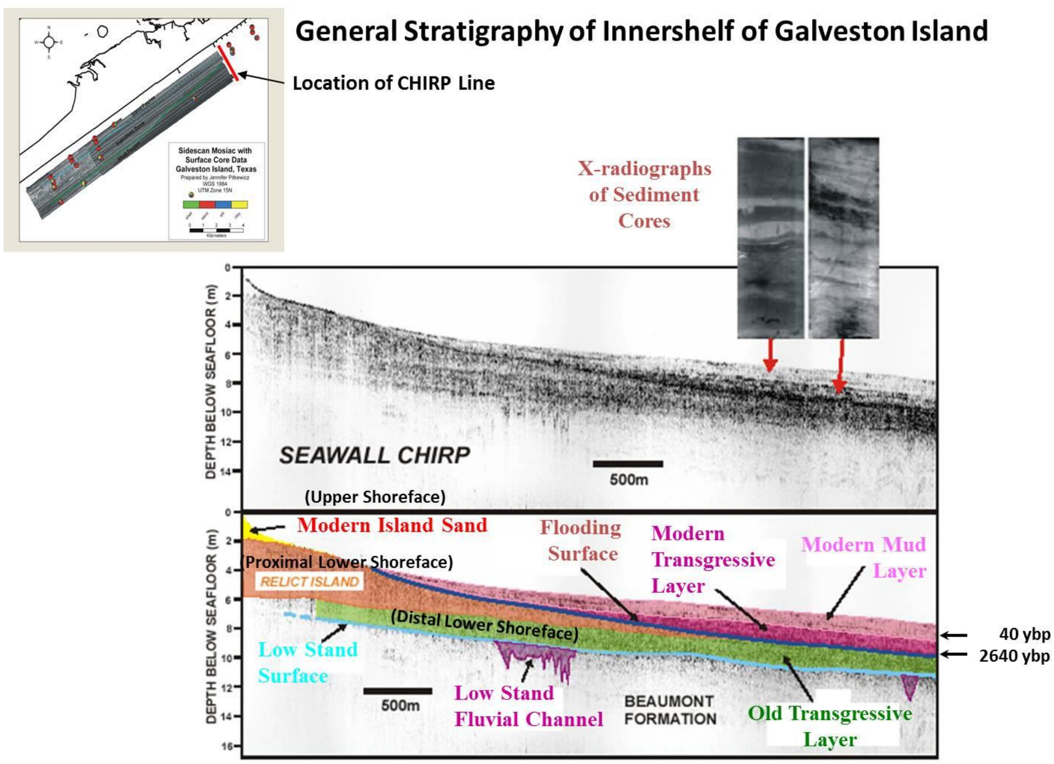
## 2.4 Environmental Setting

The Galveston Island South Jetty is 7.6 km long and was constructed at the eastern end of the island at Bolivar Roads inlet in the late 1800's. The South Jetty and its counter -part, the 10.6 km North Jetty on Bolivar Peninsula, have caused a large accretion of sand on the eastern end of the Galveston Island and the western end of Bolivar Peninsula, respectively. After the devastating effects of the Hurricane of 1900, which killed over 6,000 residents of Galveston Island, the Army Corps of Engineers constructed a 16 km long Seawall and groin system. These have further contributed to the alteration of sediment supply by causing a system of erosion and accretion, and an overall sediment deficiency in the region.

Sediment supply in this region of the GOM is also influenced by hurricanes. These short term but high-energy events affect the Texas shoreline on average every 1.5 years, and a storm that causes substantial erosion to this area occurs about every six years [*Siringan and Anderson*, 1994]. Galveston typically has southeasterly winds in the summer months and short periods of northerly winds in the winter [*White et al.*, 1985]. Average significant wave size and tidal range are 2.1 m and 45-50 cm, respectively, however during hurricanes wind direction changes and wave heights can reach wave height of up to 7 m [*Rodriguez*, 1999].

## 2.5 Previous Work

The greater Galveston Island area is very well studied. The basic geology of the offshore region has been classified into four unique facies; The Upper Shoreface, Proximal Lower, Distal Lower Shoreface, and the Modern Mud Unit (Figure 3). The Upper Shoreface consists of 80 to 100% fine to very fine sands and extends approximately 1.5 to 2 km offshore [*Rodriguez et al.*, 2001; *Siringan and Anderson*, 1994]. Surface sediments in this region have a modal size of 3 to 3.25 phi (0.125 to 0.105 mm) [*Rodriguez et al.*, 2001]. The Proximal Lower Shoreface is composed of very fine sands and medium to thickly interbedded mud layers (10-50 cm), with a silt and clay content ranging from less than 30% to over 60% at the central portions of the island [*Rodriguez et al.*, 2001]. The Distal Lower Shoreface contains predominately muddy sediment and thin to medium bedded sand layers (3-20 cm), with 55 to 75% silt and clay [*Rodriguez et al.*, 2001; *Siringan and Anderson*, 1994]. Sands within the Proximal and Distal Lower Shoreface have a modal size of 2.5 to 3.0 phi (0.177 to 0.125 mm). The Modern Mud Unit incises antecedent shoreface units and contains at least 60% silt and clay [*Robb*, 2003].




CHIRP cross-shore profile of a shoreface transect (location in Fig. 1). X-radiographs negatives (white=coarse) of typical 30 cm lengths of the modern mud and underlying transgressive mud.

Figure 3 Geology of the shoreface and inner continental shelf

Radioisotope age dating was conducted by Robb et al. (2003) using 137Cs and 210Pb to establish a geochronology at a study site offshore of the Galveston Island between 25th and 68th streets (East End) and offshore of Pirates Beach (West End). The base of the Modern Mud Layer dates to 2660 ybp and the most recent mud layer has formed in the last 22 and 57 years [*Robb*, 2003].

At the base of the modern stratigraphic sequence lies the Pleistocene aged Beaumont Clay (BC) [*Siringan and Anderson*, 1994]. It was formed during the Pleistocene high stand of sea level as clays and silts were deposited from the Trinity and Brazos rivers far from shore. Over time, sea level fell as the Wisconsin Ice age began. During this time, the rivers incised channels that cut into the BC unit and extended through the study area and to the southeast [*Blum and Price*, 1998; *Cole and Anderson*, 1982]. The resulting valley fill and alluvial plain formation provided the sands from which the formation of Galveston Island began [*Cole and Anderson*, 1982].

During the Wisconsin transgression, sea level rose, the regional sand bodies were transported landward, and Galveston Island began to emerge. Since the BC has a shear strength of 1 kg/cm$^2$, it has a high resistance to erosion and served as a base upon which the modern island lies.

The upper BC boundary is marked by a sharp increase in shear strength and a transition to mottled orange and green clay and often the presence of calcareous nodules is observed [*Bernard et al.*, 1959]. This Pleistocene sequence lies deeper towards the eastern end of the island near the ancestral incised Trinity River valley and is shallower towards the western portion of the island [*Bernard et al.*, 1959; *White et al.*, 1985]. This westward shallowing of the hard, consolidated, indurated BC corresponds with the thickness of overlying sand and mud, resulting in the thinning of the Holocene sediment towards the western end of Galveston Island. As expected, the amount of sand also decreases with the distance offshore towards the island's sand toe; which, on the western end of the island pinches out at approximately 1.5 km offshore [*Robb*, 2003].

The seaward extent of the island toe is also the depth of closure according to Swift (1985) and Rodriguez (1999). The depth of closure is the depth of the wave base; the depth at which wave energy no longer can create enough shear stress to erode sand [*Swift et al.*, 1985]. The wave base depth is demarcated by a change from a sand dominated to a mud dominated seabed. Consequently, there is also a change in slope at this point, since coarser sediment will form a steeper slope while finer sediment will create a gentler slope. Since the BC is a hard, indurated clay, it is extremely resistant to erosion. Consequently, the volume of sediment above the BC is effectively all that can be considered mobile in this system, so this boundary dictates much of the morphology of Galveston island in a manner similar to the antecedent geology for the East Coast of the United States, where the Pleistocene surface also creates and erosional barrier [*Belknap and Kraft*, 1985; *Thieler et al.*, 1995].

There are multiple studies quantifying beach erosion rates on Galveston and discussions of beach nourishment happen very regularly. These studies show long-term beach erosion has occurred on the West End of the island. Rates were up to 4 m/year from just west of the end of the Galveston Seawall to Bermuda Beach [*King*, 2007; *Morton and Paine*, 1985]. Erosion is significantly enhanced after hurricanes, increasing rates to 6 m/year just past the end of the Seawall and towards the western most end of the island [*Morton and Paine*, 1985].

More recently, two papers have been presented looking at longshore sediment transport rates, sources, and sinks to integrate that data with the shoreline erosion and accretion. These studies show longshore transport estimates of 170,000 $m^3 y^{-1}$ into the Galveston Island system, 139,000 $m^3y^{-1}$ out of the system to the west, and 115,000 $m^3y^{-1}$ sequestered in the shoreface (Figure 4) [*Morang*, 2006; *Wallace et al.*, 2010].

From 2001 to 2006, the Coastal Geology Lab at TAMUG collected, side scan sonar, multibeam swath bathymetry, and submersible vibra cores between the 3 and 10m isobath. This data is the baseline or control for pre-storm conditions described in this paper (Figures 5 & 6).

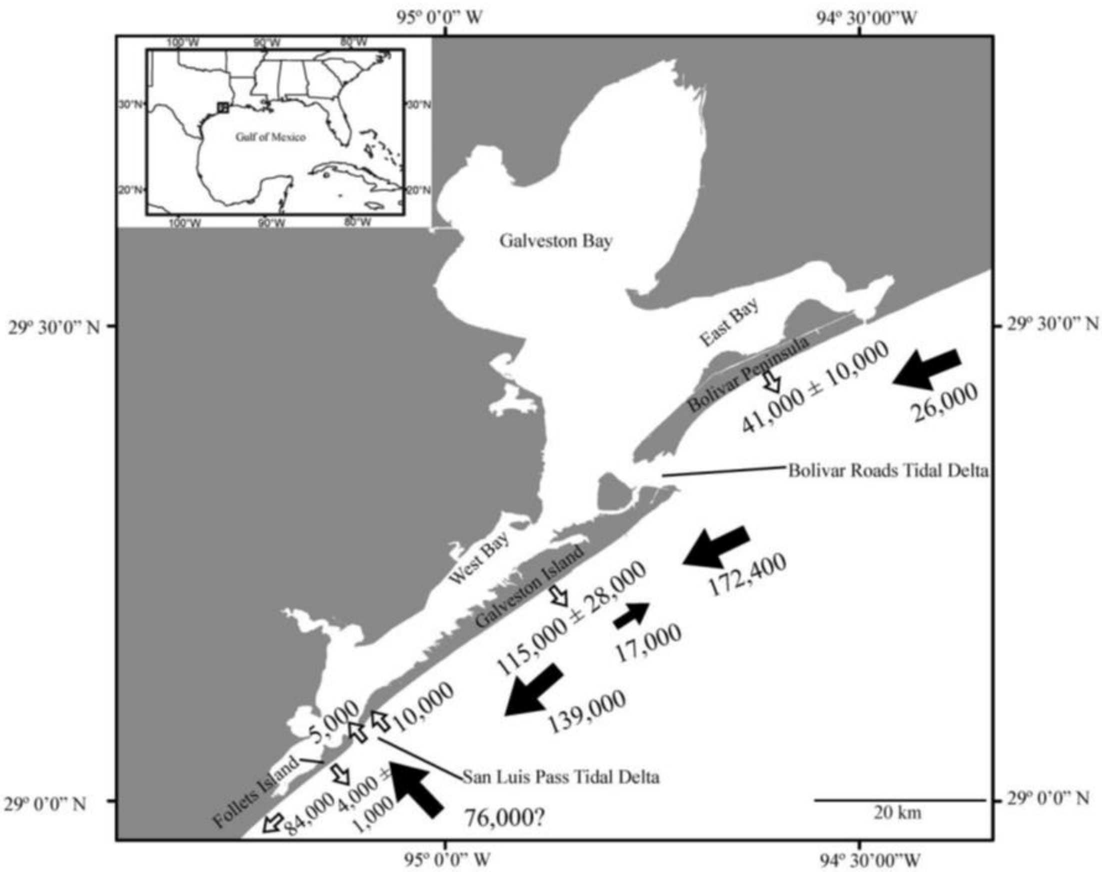



Figure 4: Approximate longshore transport and offshore sediment fluxes. From Wallace et al., 2010

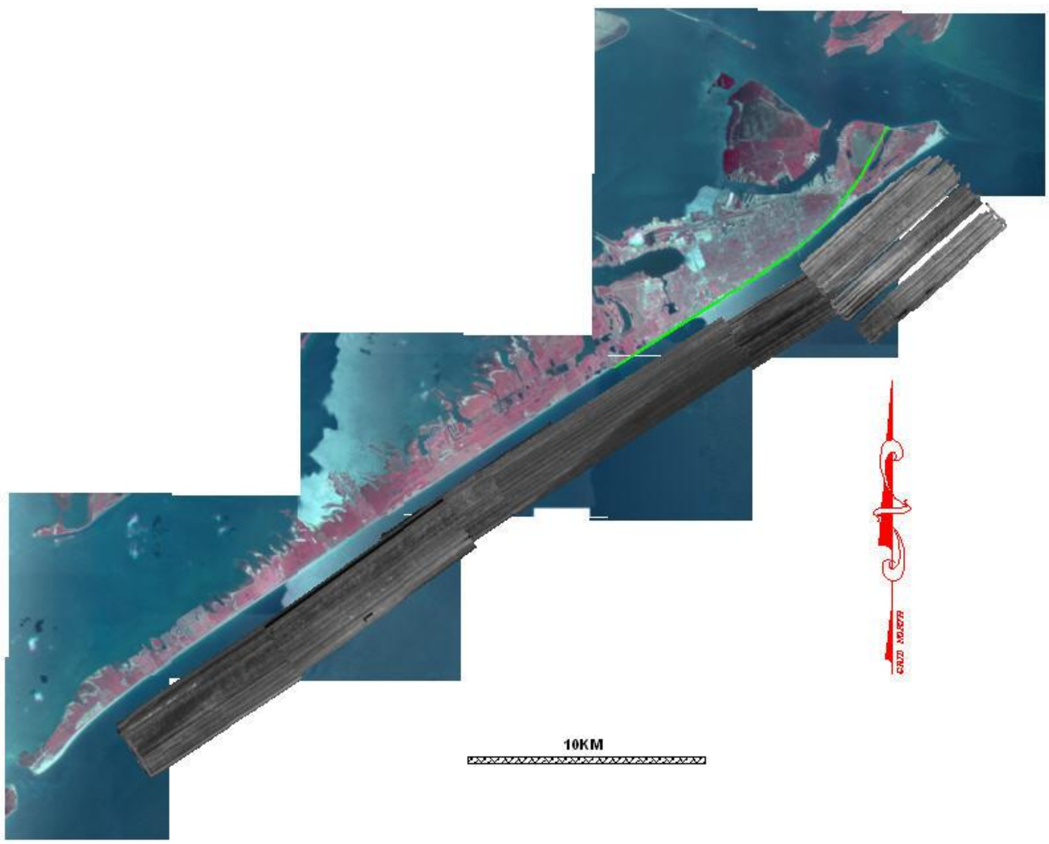



Figure 5: Side scan sonar mosaic completed in 2006

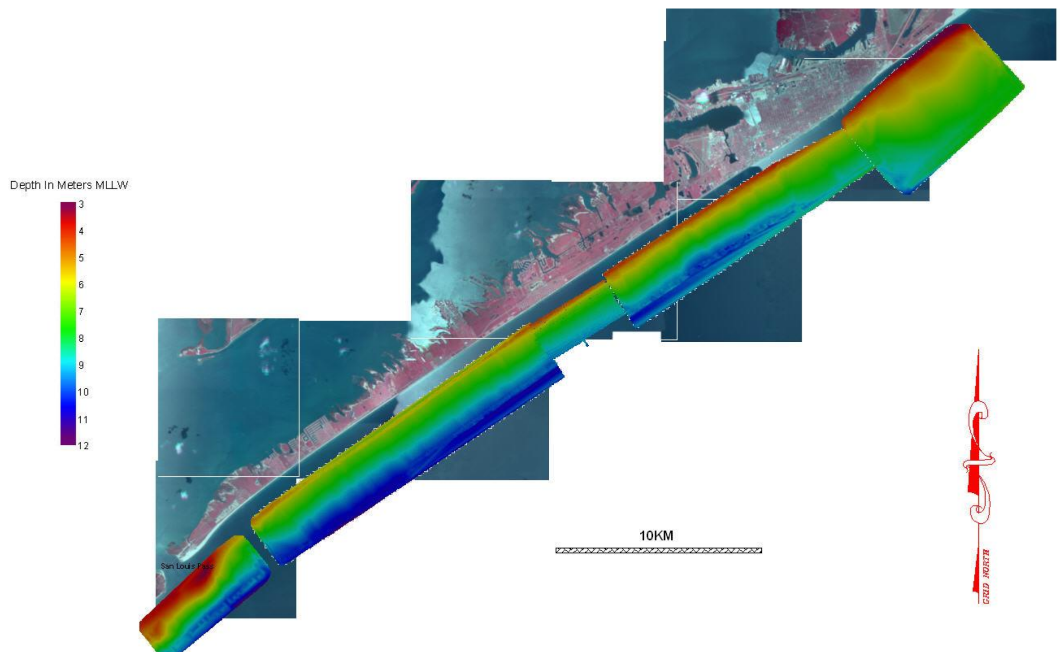



Figure 6: Galveston Island bathymetry completed in 2006

# 3. METHODS

## 3.1 Geophysical Surveys

The Galveston Shelf Survey, conducted in September and December of 2010, extended from near the Galveston Jetties in the east to near San Luis Pass in the west. The survey was conducted aboard the NOAA Flower Garden Banks National Marine Sanctuary (FGBNMS) Ship R/V Manta in water depths from the 3 m to 10 m isobath based on NOAA nautical charts (Figure 1). Survey lines were oriented parallel to the shore using Hypack® 2009a Coastal Oceanographic software. Lines were spaced 100 meters apart giving 200% coverage for the side scan data and approximately 60% coverage for the bathymetry data based on the manufacture specifications for the Benthos C3D system used. The total length of the surveys was 1922 km. Survey data was collected in the WGS 1984 datum and projected into UTM Zone 15 North coordinates. The horizontal and vertical data are in meters. The bathymetric data was corrected to mean low water (MLW) using NOAA tide station 8771450 located on Pier 21 in Galveston (Red star in Figure 7).

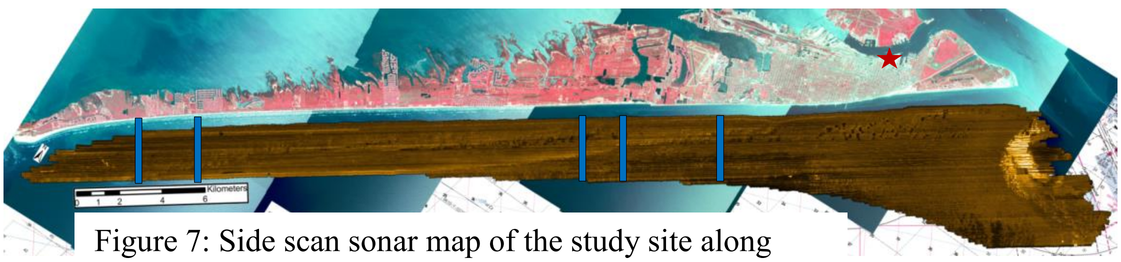



Figure 7: Side scan sonar map of the study site along Galveston Island Texas. Pier 21 tide monitoring station marked with the red star. Cross-Shelf profiles designated by blue bars.

Side scan sonar (SSS) and bathymetric data were collected concurrently using a Teledyne Benthos® C3D-LPM High-resolution side scan sonar bathymetric system. This sonar utilizes two transducers operating at a frequency of 200 kHz coupled with a six hydrophone array receiver collect the SSS data, and bathymetric data is computed by the sonar using the computed Angle of Arrival Transient Imaging (CAATI) algorithm. The sonar was pole-mounted to the bow of the vessel, position of the vessel was determined using a Hemisphere® Vector differential GPS, and ship motion data was determined using a SG Brown TSS® DMS3-05 motion reference unit to correct the bathymetric data collected. Periodic casts with an Odom® Sound Velocity Probe were conducted to collect sound velocity data throughout the water column to also correct bathymetric data. Sonar data was acquired using Hypack® Hysweep 2009a software.

Bathymetric data was processed using Hypack® Hysweep 2009a software, where tidal, ships motion, and sound velocity data were integrated to correct the raw bathymetric soundings. SSS data was processed using Chesapeake Sonar Wiz.Map® software to create and export SSS mosaics.

## 3.2 Sediment Data

Sediment cores were collected from both study areas in September of 2011 aboard the NOAA FGBNMS R/V Manta, 22 from the Galveston Shelf Study. The cores were 7.62 cm (3 in) in diameter and on average 1 m of sediment were recovered. These cores were collected using a pneumatic submersible vibra-core rig deployed off the stern of the vessel. Cores were stored upright and refrigerated until analyzed. Surface sediment grab samples were also collected from the study site. The locations of these physical samples are arranged in shore- perpendicular transects ordered from East to West in alphabetical notation (Figure 7 & 9).

Cores were cut lengthwise, photographed, and visual descriptions of the sediment lithology were recorded. One-half of each core was archived for future reference and one-half processed for water content and grain size analyses. Cores were sub-sampled for every lithological unit as determined by visual analysis in sections ranging from 1 – 5 cm thick depending on the unit for the length of the core, and placed into labeled Whirl-Pak bags until analyzed.

Sediments samples were analyzed in the lab for grain size distributions using a Malvern Mastersizer 2000® laser particle diffractometer. Sediment samples were homogenized, and an approximately 3-5 g aliquot was placed in a 100 ml glass jar. Ten milliliters of a 5.5-g/L sodium hexametaphosphate solution was added to the jar as a dispersant. The sediment with dispersant was sonicated for 30 min. at a temperature of approximately 25°C at a frequency of 40 kHz. After sonication, samples were wetsieved through a 2 mm sieve into a 250 ml glass jar, and material larger than 2 mm was placed in a pre-weighed aluminum dish, dried for at least 24 hours, and then weighed. The sample slurry in the 250 ml glass jar was filled with de-ionized water to a volume of exactly 200 ml then placed on a stir plate. While the slurry was stirring, a representative 10 ml aliquot was removed by a pipette and placed in a pre-weighed aluminum dish and dried for at least 24 hours then weighed. After the 10 ml aliquot was removed, the slurry was pipetted into the Malvern Mastersizer 2000® until a pre-determined level of obscuration was reached. At this point the instrument made three measurements and averaged the three results. The instrument determined percent composition of sand, silt and clay of the samples, and from the 10 ml aliquot that was removed and the material excluded during the wet-sieving process, the percentage of material greater than 2 mm was calculated. In total the fraction of gravel, sand silt and clay were determined for each sample, as well as the mean grain size of the sand fraction.

# 4. DATA & RESULTS

## 4.1 Baseline Data

The data from 2006 is limited to those shown in Figures 5 & 6 and the accompanying reports produced for the TGLO and Scott Hiller's unfinished thesis [*Dellapenna et al.*, 2006]. Despite the limitations, there is still important baseline details in this data. Prior to Hurricane Ike, the inner shelf of Galveston Island was observed to be a homogenous surface with few unique characteristics. The shore perpendicular profiles extending from onshore to offshore show a steady decrease in slope from East to West in two distinct zones, the section of Galveston Island in front of the seawall and the "natural" west end.

The baseline bathymetry (Figure 5) presents a similar story to the profiles; two zones of west to east increase in slope, separated by the end of seawall. Additionally the effect of the seawall is quite evident by the large scour region directly offshore of the end of seawall.

The grain size data shows a predominately sandy seabed inshore that progresses to a mud dominated offshore, exactly as described by Robb (2003) and Anderson (2002).

## 4.2 Post-Storm Data

The data collected after Hurricane Ike, shows a very different shoreface than the baseline data set. Some of the more obvious changes are the large areas of scour pits, the off-lapping shoreface sands over offshore muds, the large scale bar and trough region (Figure 8), as discussed below.

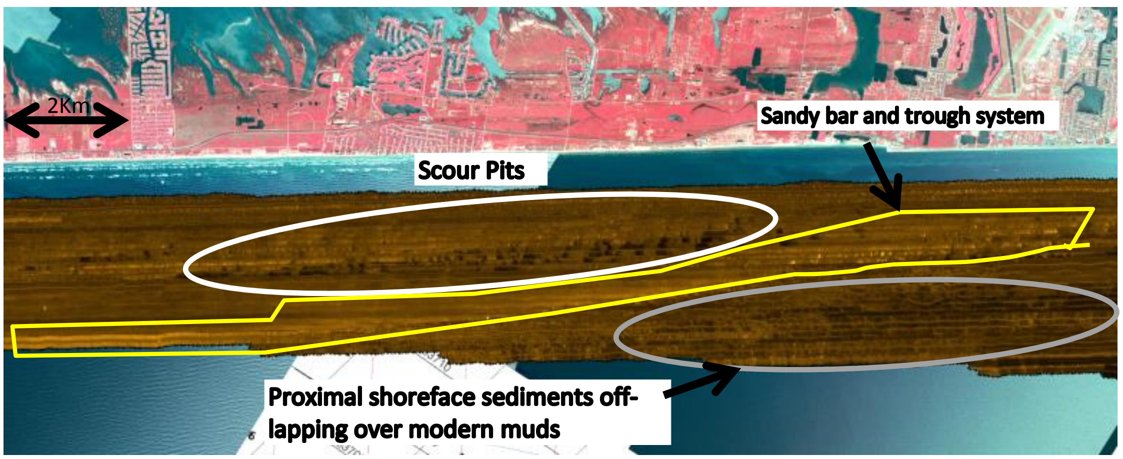



Figure 8: Examples of seabed features observed in the post-Ike data set

The sides scan sonar shows several zones of unique backscatter characteristics. Darker zones are due to lower backscatter or more absorption of the sonar pulse into the seabed, where lighter toned areas are places with a higher backscatter or more reflection of the sonar pulse from the seabed. The intensity of the backscatter in this survey was ground-truthed using an average over the top 5 centimeters of sediment from each core site. The results from that ground-truthing showed that the areas of higher backscatter had higher sand content and the lower backscatter areas had lower sand content. Using these interpretations, the surface expressions of the facies identified in Figure 3 were delineated, including the Modern Island, Proximal Lower shoreface, and Modern Offshore Mud Facies.

The most direct method to compare the baseline dataset from 2006 to the post-storm dataset is to simply display them side by side. Figure 1 is an annotated offset comparison of the two surveys. The 2006 baseline survey is in its true location with the post-storm 2011 survey offset to the southeast, which is outlined in green. The yellow annotations indicate via number the location and letter the survey. “A” represents the initial reference from 2006 and “B” represents 2011.

- 1A is not present as the survey in 2006 did not cover this area but 1B shows a bright area in the side scan that represents a large sandy depression which is the remains of a United States Army Core of Engineers dredge spoil dump site.

- 2A is not present in the baseline survey but 2B shows the transgressive offshore muds overlapping the general proximal shoreface sands located throughout this region.
- 3A is also not a part of the initial survey but 3B shows a series of dark spots that are depressions in the shore face with fine grained muds filling the low centers.
- 4A marks a dark area of offshore modern muds that are covered in a veneer of sand and a sand bar in 4B.
- 5B shows the development of the offshore sandbar and trough system on the proximal lower shoreface represented in 5A.
- From 6A to 6B the sandbar and trough development is continued along with the formation mud pits similar to those located in 3B.
- From 7A to 7B there is a veneer of sand deposited and the sand bar and trough system is continued through this section as well.
- The change from 8A to 8B shows a combination of a scour feature and the continued development of the offshore sandbar. It is at this point where the sandbar extends beyond the survey depth.
- 9B shows a dark muddy region that is not present in 9B either through burial in shoreface sands or removal due to physical transport.

Post-Ike bathymetry data in general is very similar to the pre-storm baseline conditions from 2006. The east to west gradient of increasing slope is still present for the east half of Galveston Island, but the western half has a more uniform slope, unlike the baseline dataset.

The areas highlighted from the side scan data are also areas of unique bathymetry. The regions labeled as scour pits are in fact bathymetric lows and are identified as such by this dataset. The sandy bar trough system extending through the middle of the survey is less visible but still present on the gradient map.

The bathymetry data alone is less helpful for this particular study because the raw data from 2006 is not available, so quantitative analysis of shoreface volume changes is less straightforward. However, I was able to use the unique bathymetric features with the ground truthed side scan data to accurately estimate the volume of upper shoreface sands that were transported offshore within the sand bars presented with the sediment analysis in section 4.2.5.

The east end of the survey proximal to the South Jetty of Bolivar Roads has the highest sand content in the surface sediment of the entire survey area (Red triangle in Figures 9). The bright patch on the sides scan is part of a bathymetric low. The surface sand content decreases with distance from this zone and is shown to be part of a veneer (less than 5cm) over the offshore modern muds identified by the baseline study.

There is a long bright feature extending from the 3m isobath offshore from 61st street offshore in a southwesterly direction to beyond the survey depth at the “G” core transect (Offshore of Terramar Beach). This feature is a sandbar identified in figure 16 as numbers 1, 5, and 6 which contains a large amount of sand in the surface sediments and is not present in the 2006 baseline dataset (Figures 1 & 12).

To better visualize relative sand content in the upper 5 centimeters the intensity of the return after ground-truthing was assigned a range of sand content and displayed in a false color map (Figure 9). Due to the range of sand content found in the core samples and the correlating range of intensities the range for each color is large. This data is farther simplified in Figure 10 to show the regions of greater than 70% sand sized sediment in the upper 5cm.

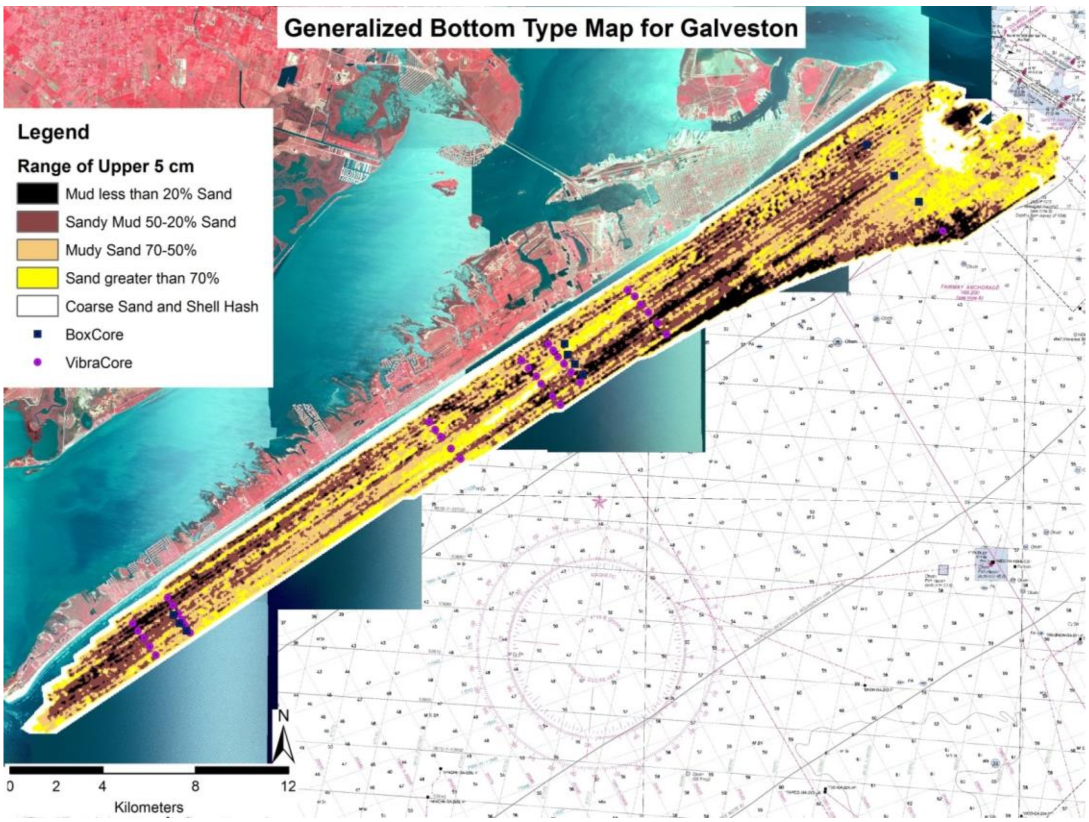


Figure 9: Integrated surface backscatter for generalized bottom type

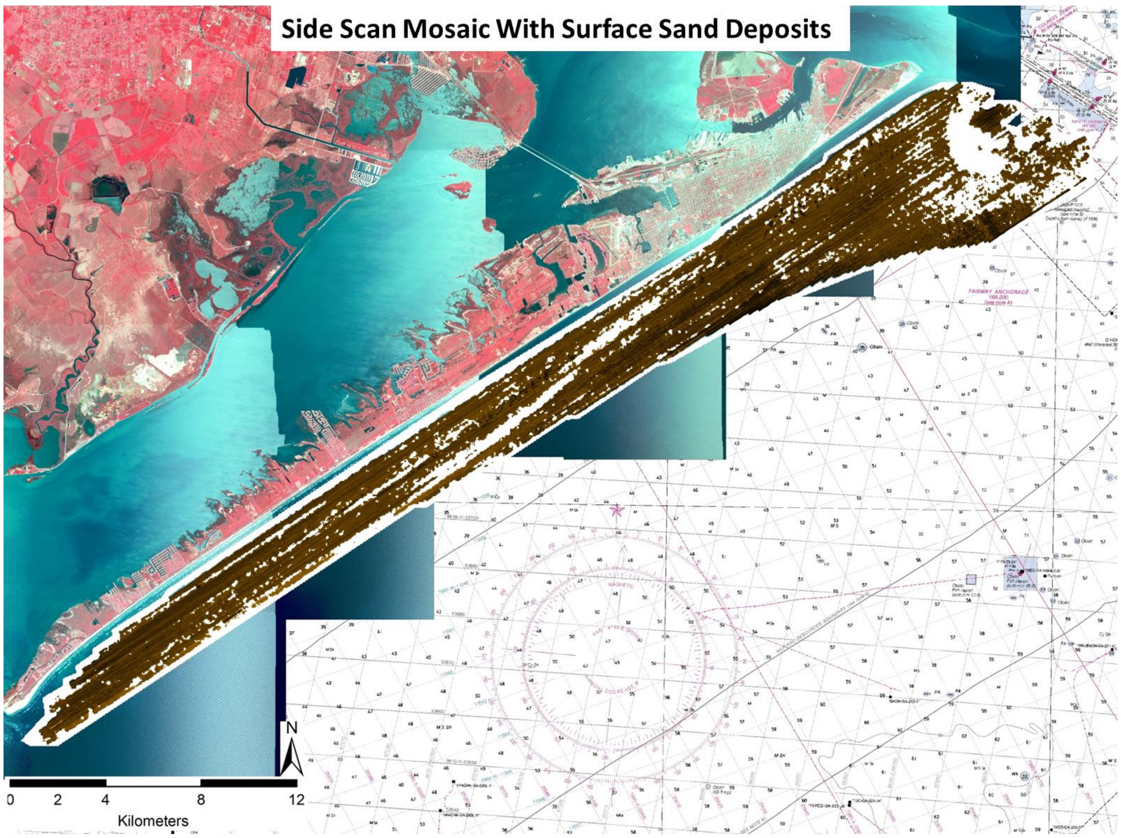


Figure 10: Side scan sonar mosaic with upper shoreface sands highlighted. White areas indicated greater than 70% sand content in upper 5cm.

Physical sediment samples were collected in strategic transects along Galveston Island as shown in figure 1. In general the surface sediment distribution is the same as described by Robb et al. (2003). However there are areas where deviation from the previously described surface sediment distribution is observed. The trend of fining sediment with distance offshore is mostly consistent, but not in the areas where beach sands were transported offshore due to Hurricane Ike. This includes the previously described sand bar system and offshore deposit near the South Jetty.

In order to accurately visualize, analyze the study site, and produce estimates for sand volumes to determine if the hypothesis is correct, cross-sectional profiles were generated (Figures 11-15). There is an individual profile for each core sample transit and the physical description of each core has an arrow indicating its respective location relative to the first core in each transit. The vertical scale on the left side of each figure shows the bathymetric depth in meters. The horizontal scale is the distance in meters to the first core in each profile.

The average slope for the profiles ranges from 0.012 for the GSE transect to 0.381 for the GSH transect (Figures 13 and 15). In general the slopes are shallow (0.012-0.077) in the middle section of the survey and increase to steeper angles at both the east and west ends (0.365). In addition to the general slope change, the profiles have ridges and troughs that are part of a large set of sandbar troughs throughout the majority of the survey. These large-scale sandbars represent almost 10% of the total survey's surface area. Using the bathymetric profiles, patterns in the side scan data, and the depth of sand for these features from the sediment cores, surface sand volume estimates were generated for each distinct sandbar (Figure 16). This process for estimating resulted in a fairly wide range of values. The lower end value is based on the absolute minimum possible amount of sand that could be present in each region based on the ground-truthed side-scan return intensity maps, known values for depths of sand within each sand bar, and finer scale binning of spatial data for the volume calculations. The large end estimation is based on a coarser binning of data, with reasonable assumptions for depths of sand where physical samples were not always present. This estimation also included core samples that were disturbed enough, or had data gaps, to where they no longer were suitable for absolute measurements, but were enough for confidently assuming a maximum possible depth of surface sand.

The approximate location and known depth from recovered physical samples is drawn into the profiles in Figures 11-15 as the yellow polygons near most bathymetric highs along the profiles. The data for these comes from the cores collected for this study. Many areas had incomplete or intervals with losses in the core. While these samples were not used for quantitative depths or analysis, they were used to help estimate the depths of surface sands shown in these profiles. While depths and locations are estimates, they are drawn to scale as much as the limitations of this study, and the bathymetric profiles will allow.

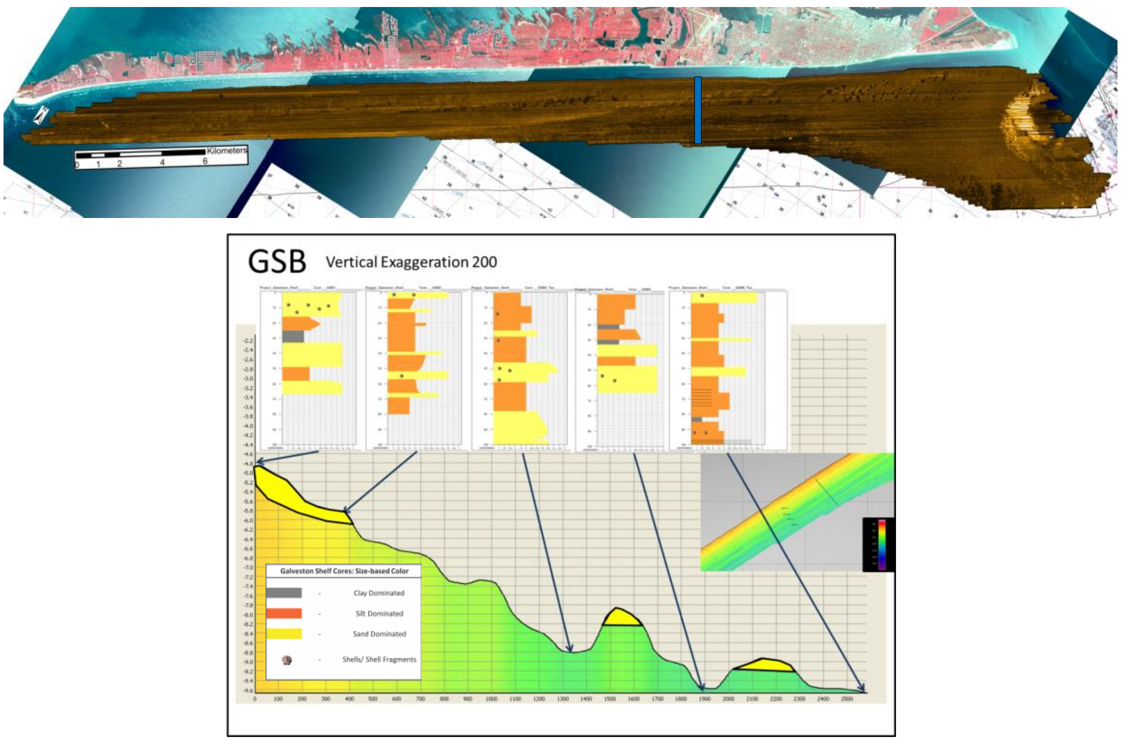



Figure: 11 Cross-shelf profile GSB. Approximate depths and locations of surface sand deposits masked in yellow on the profile. Core plots are displayed with arrows indicating estimated collection location.

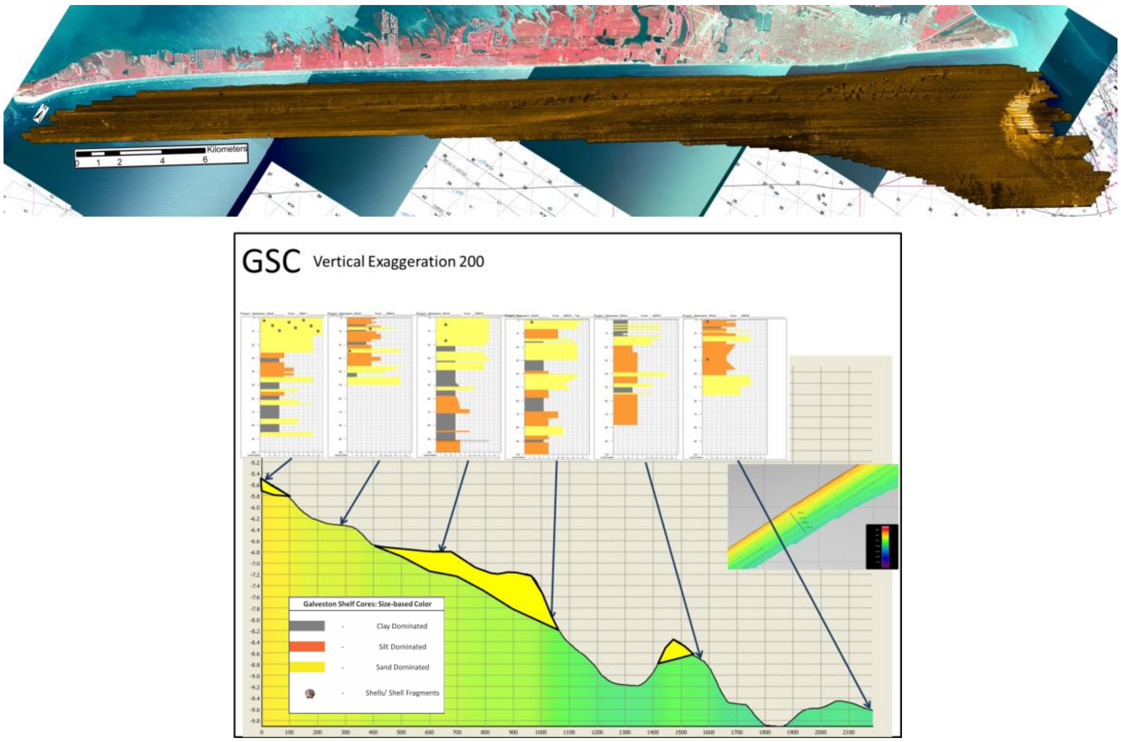



Figure: 12 Cross-shelf profile GSC. Approximate depths and locations of surface sand deposits masked in yellow on the profile. Core plots are displayed with arrows indicating estimated collection location.

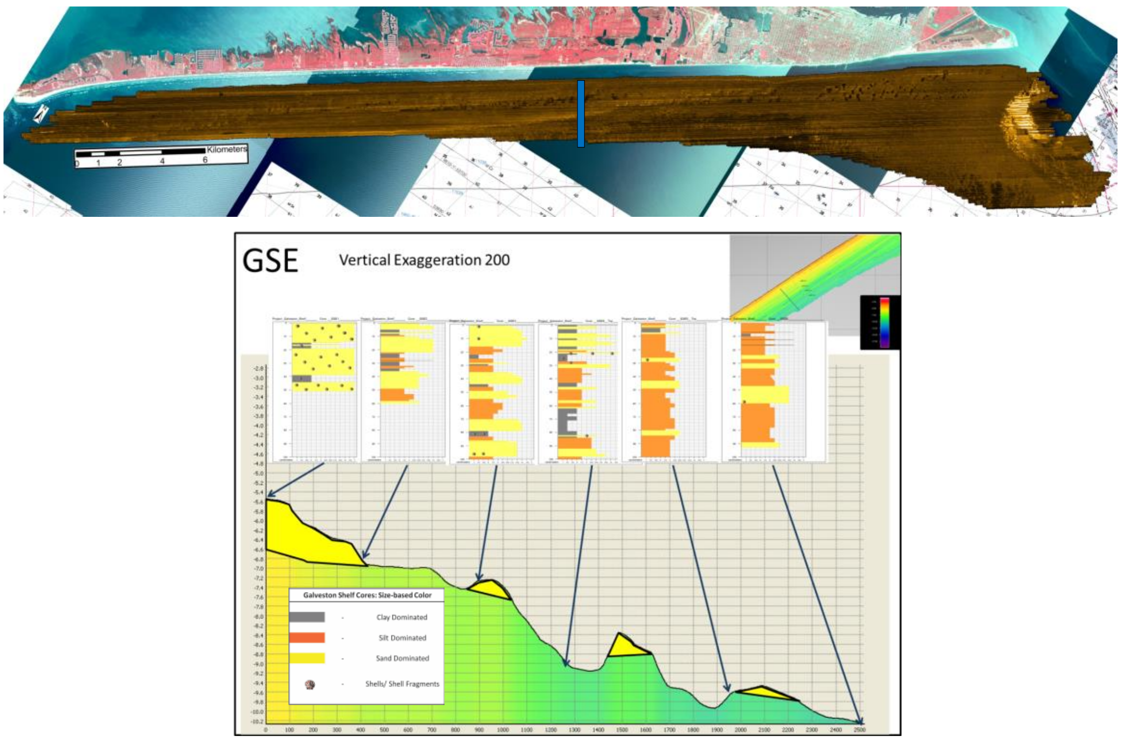



Figure: 13 Cross-shelf profile GSE. Approximate depths and locations of surface sand deposits masked in yellow on the profile. Core plots are displayed with arrows indicating estimated collection location.

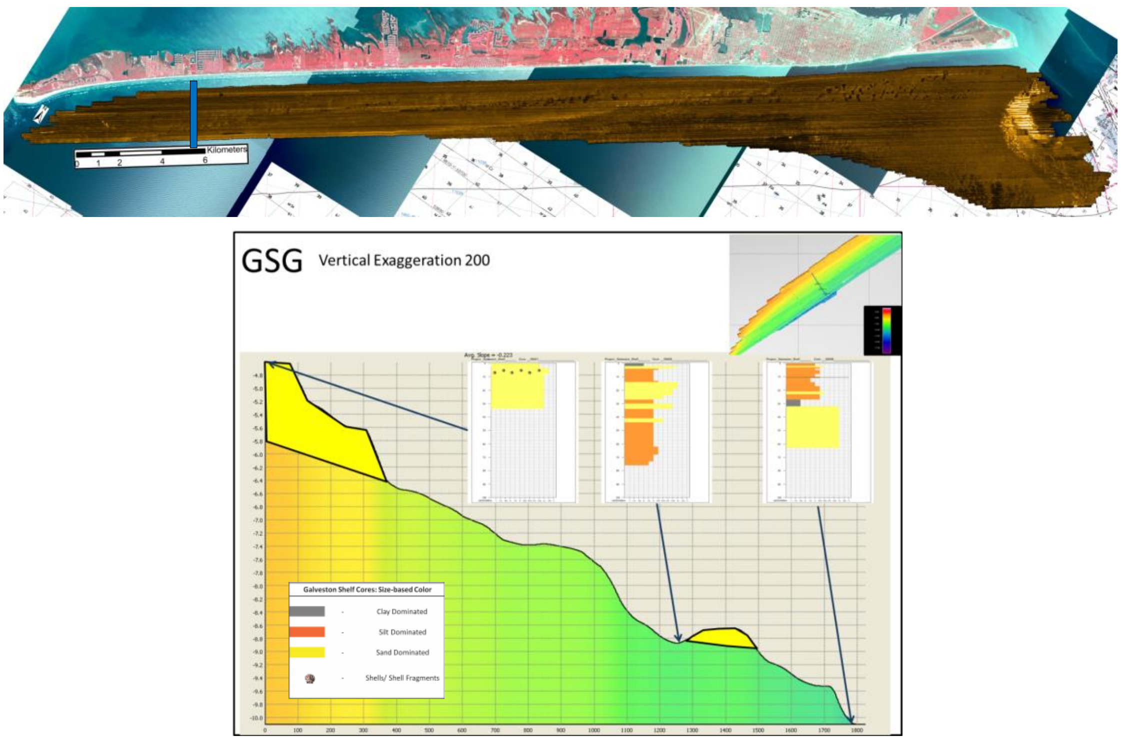



Figure: 14 Cross-shelf profile GSG. Approximate depths and locations of surface sand deposits masked in yellow on the profile. Core plots are displayed with arrows indicating estimated collection location.

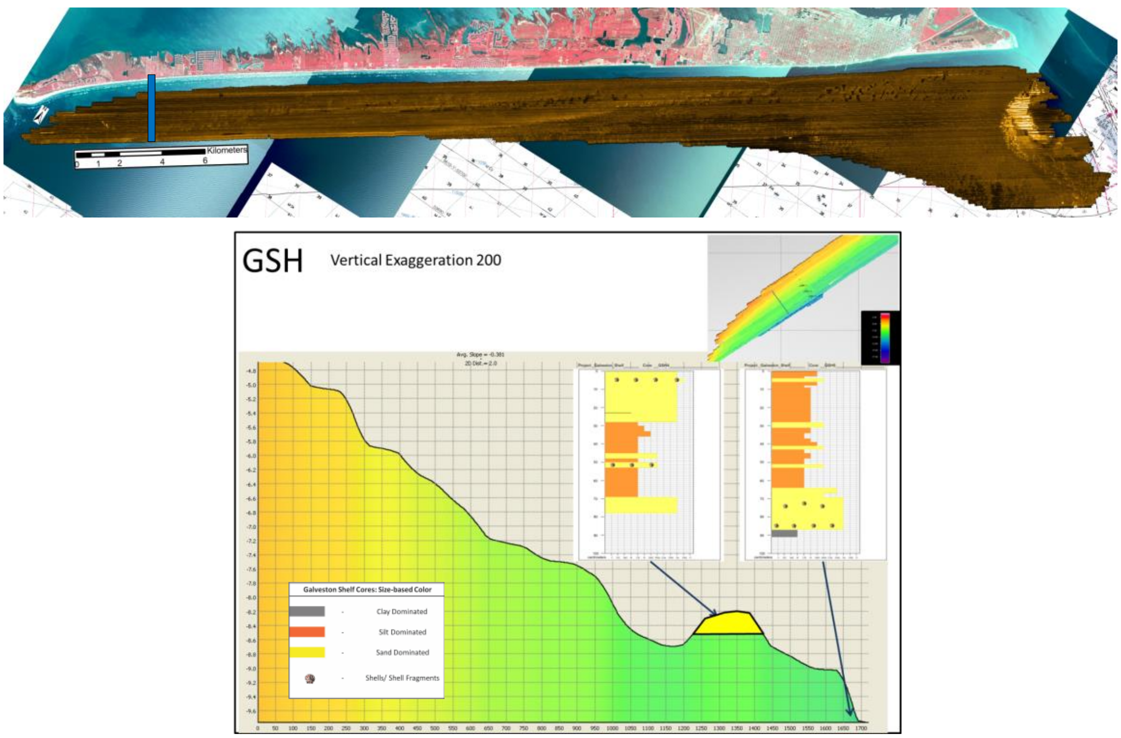
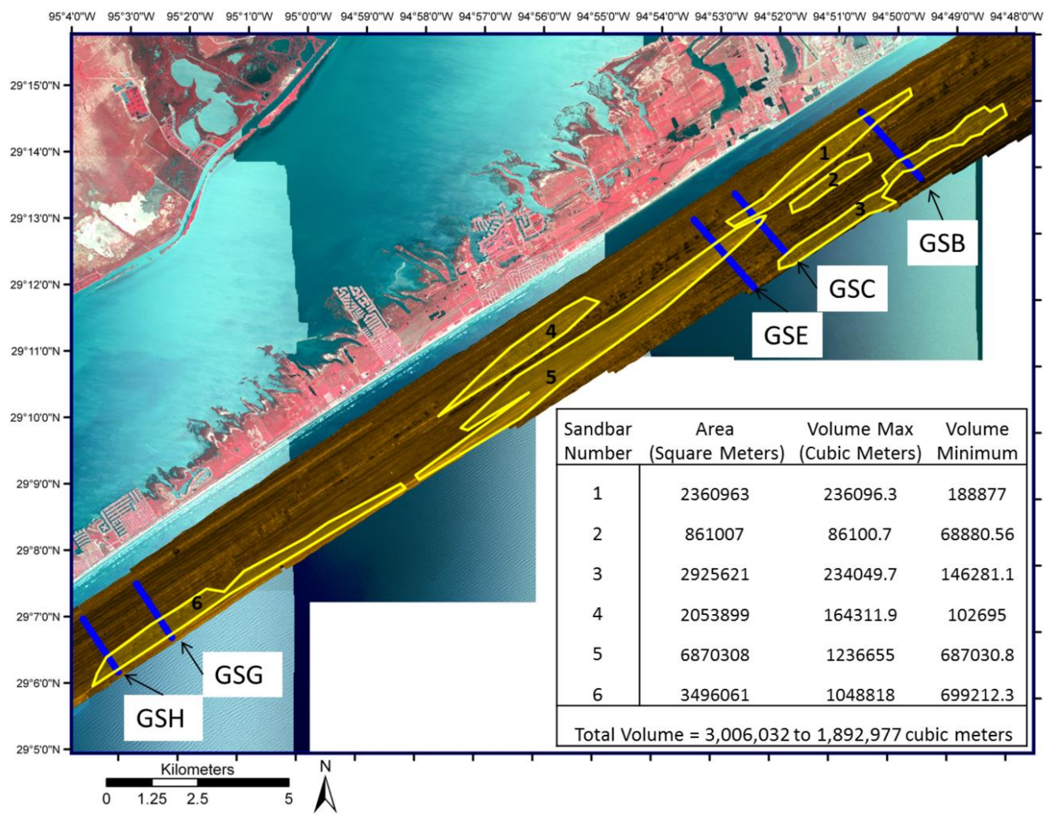



Figure: 15 Cross-shelf profile GSH. Approximate depths and locations of surface sand deposits masked in yellow on the profile. Core plots are displayed with arrows indicating estimated collection location.




| Sandbar Number | Area (Square Meters) | Volume Max (Cubic Meters) | Volume Minimum |
|---|---|---|---|
| 1 | 2360963 | 236096.3 | 188877 |
| 2 | 861007 | 86100.7 | 68880.56 |
| 3 | 2925621 | 234049.7 | 146281.1 |
| 4 | 2053899 | 164311.9 | 102695 |
| 5 | 6870308 | 1236655 | 687030.8 |
| 6 | 3496061 | 1048818 | 699212.3 |
| Total Volume = 3,006,032 to 1,892,977 cubic meters | | | |

Figure 16: Offshore sand bar volume with labeled core transects

## 5. DISCUSSION

When comparing the two data sets, the post-Hurricane Ike survey reveals extensive scour troughs and pit across the study area suggesting extensive erosion, as well as broad deposition of a relatively thin, sand-dominated storm layer (18 cm average thickness) across much of the study area. In addition to the thin sandy storm layers, six large sand bars identified in Figure 16 contain an estimated total of between 1.8 - 3 million $m^3$ of sand. The reason for the large range is the surface area of these sandbars is quite large, so a few centimeter difference in depth of the surface sand deposit results in a large volume change. The higher estimate is produced using the actual depth of surface sand measured for each sand bar from actual core samples collected from each sand bar. The lower estimate used a shallower assumed average depth of sand for each feature to compensate for volume changes from tapering at the edges of each sandbar. The resulting volume of surface sands is distributed over 10% of the total survey area. These new sand layers reveal sand further out on the shelf than was found in the pre-Ike surveys.

In addition to the sand bars, overall, there is a large deposit of sand off of the eastern end of the island, proximal to the South Jetty, indicating extensive offshore sand transport from East Beach. Unfortunately, the sand created a hard seabed in this area and the box-cores and vibra-cores were not able to recover cores long enough for complete computation of the volume of sand present in that area. Based off of the trends seen in the rest of the survey in the side scan, physical samples, and bathymetry, it seems like the USAE dredge deposit site (located in this region, as noted above) has been physically sorted, removing much of the mud and leaving sand behind in a bathymetric low. This site covers an area larger than $4x10^6$ $m^2$ making it almost twice as large as the largest sand bar (#1 Figure 16) or roughly 2% of the entire survey area. Although none of the physical samples in this area fully penetrated the surface sand layer, one core recovered was 15cm deep. Assuming uniform coverage of at least 15 cm the USACE dredge deposit site contains at least $6.0x10^5$ $m^3$ ($7.92x10^5$ $y^3$) of sand (likely a large under estimate). Near this same area, Goff et al. (2010) documented the storm-surge ebb tide from Hurricane Ike through Bolivar Roads tidal inlet, just north of the South Jetty. They documented “Shoreface sands appear to have been incised by the storm, and advected with beach-barrier sediments sufficiently offshore by the storm-surge ebb that they cannot be reincorporated into the beach, indicating a significant loss to the barrier system’s sediment budget as a result of a single storm.” They also found significant offshore and shore-parallel flow of up to 60 cm $s^{-1}$ during the week after Hurricane Ike [*Goff et al.*, 2010]. With these flow rates it is easy to see how the large regions of sand documented in this study could be transported and sorted.

The total volume of recently transported sand sitting on the seabed in the upper 50 cm of the seabed is estimated to be between 1.8 $x10^6$ and 3 $x10^6$ $m^3$. This volume of sand deposited offshore during one major event is much larger than the annual rate of longshore transport. To bring this number into context, the published annual sediment transport rates for this region of the Texas coast suggest that only $1.15x10^5$ $m^3$ $y^{-1}$ is transported to the inner shelf from the shoreface [*Wallace et al.*, 2010]. This discrepancy in volume shows that if there were no other sediment transport to this sink, this one event would account for between 16-26 years of the annual flux. Under storm conditions, Ravens suggested $4.0 \times 10^5$ $m^3$ of sand would be needed to maintain the 2001 shoreline on Galveston Island [*Ravens and Sitanggang*, 2007]. This value is closer to what I observed, however it accounts for less than half of what was measured under storm conditions, and therefor is likely still an underestimate. The estimation for annual sequestration rates on the shoreface of Galveston Island (0-10m isobath) of $1.43 \times 10^5$ $m^3$ $y^{-1}$ based on combined datasets form several recent studies also falls short of what was measured in the sand bars formed during Hurricane Ike by 3 to 5 times.

The discussion of depth of closure encompasses far too many aspects to be addressed fully by this research and especially so by this paper. It is worth mentioning however that based on the existing discussions of how to define that point, which includes at what water depth and over what time interval should the depth of closure be determined, this study agrees with the geology based argument for a deeper depth of closure. This study demonstrates transport of a significant volume of sediment, in water deeper than the previous 4m estimation of depth of closure. Specifically, this study documents that significant transport occurred at depths at least as great as 10m, and is likely to have occurred at even greater depths. This means that if conditions similar to what was observed during Hurricane Ike reoccur at any measurable time interval, it needs to be included in the discussion of depth of closure and long-term erosion rates for the upper Texas coast.

# 6. CONCLUSION

The volume of sand transported offshore, during Hurricane Ike is much larger than the measured and modeled longshore transport rates for Galveston Island. These pre-existing measurements suggested $4x10^5$ $m^3$ $y^{-1}$ of sand would be required to maintain the 2001 Galveston Island shoreline under storm conditions. Under normal conditions for the upper shore face (4-8m isobaths) $1.15x10^5$ $m^3$ $y^{-1}$ is sequestered and for the whole shoreface (0-10m isobaths), 1.43 $x10^5$ $m^3$ $y^{-1}$ is a conservative estimate.

This data shows the formation of storm-generated features such as large-scale sandbars, scour pits, and a widespread storm layer across the innershelf and shoreface of Galveston Island.

These sandbars contain between $1.8x10^6$ and $3x10^6$ $m^3$ of sand. Averaged over the 4-year interval from 2007-2011, the average sediment sequestration for the interval below fairweather wave base is $7.5x10^5$ $m^3$ $y^{-1}$. This means that the volume of sediment contained within the Hurricane Ike bars is between approximately 3 and 5 times the estimated annual shoreface sediment sequestration, confirming the hypothesis. Measurements further reveal that the volume of sediment stored within the Hurricane Ike bars is almost twofold (1.8x) the estimation for storm conditions beach maintenance and approximately 2-3 times higher than the estimated sediment flux from Sabine Pass to San Luis Pass.

This adds into the growing volume of literature that demonstrates hurricanes as a primary environmental mechanism for barrier island evolution. In the scope of island management these numbers, compounded with the accelerated shoreline retreat that has been observed in the Anthropocene, indicate that barrier islands are an increasingly vulnerable and highly dynamic part of the coastal system.

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